2-D AND 3-D RESISTIVITY FOR LOCATING VOIDS BENEATH HIGHWAYS; THREE CASE STUDIES

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ABSTRACT- The US Department of Energy National Energy Technology Laboratory (NETL) has successfully used DC resistivity to delineate potential subsidence zones beneath highways that are caused either by underground coal mines or nearby marble/limestone quarries. Three sites are discussed in this paper: 1) a segment of Interstate 70 in Ohio where ground subsidence into an underlying coal mine has resulted in an injury; 2) a roadway in eastern Maryland where the sudden opening of a sinkhole resulted in a fatality; and 3) a heavily traveled secondary roadway in central Pennsylvania that is prone to sinkhole development. The Ohio site (Interstate 70) has been intensely studied using seismic, ground penetrating radar, and exploratory drilling. At this site, a 2D resistivity profile acquired along the eastbound lane detected breaks in the overburden above the mine that exactly matched mine subsidence faults identified in seismic profiles. These fracture zones are areas where sinkhole development has occurred or is likely. The Maryland site is adjacent to a marble quarry near the city of Westminster. A 30-ft wide sinkhole that abruptly opened in a nearby section of roadway was responsible for one fatality. This failure-prone roadway overlies karst terrain that is being destabilized by groundwater pumping at a nearby marble quarry. A 2D resistivity profile along this highway identified bedrock platforms and pinnacles, bedrock depressions, and air-filled, clay-filled, or water-filled voids. The information from this survey has allowed subsidence mitigation efforts to be concentrated on more failure prone areas. The third site is a roadway beside a limestone quarry near Ephrata, Pennsylvania. A 2D resistivity profile parallel to a secondary highway at this site showed the location of a cave. An exploratory drill hole into the cave encountered water; two catfish were blown out of the hole during drilling. It was obvious that the fish had traveled from the Conestoga River on the opposite side of the road through cave passages beneath the highway to the drill hole site. A planned 3D resistivity survey will more accurately delineate the cave system at this site.

Introduction

DC resistivity is the predominant method used by the National Energy Technology Laboratory (NETL) to identify near-surface voids associated with mining activities. Mining related voids include: 1) underground mine workings, 2) voids that form by mine subsidence, 3) voids formed by the piping of overlying, unconsolidated material into mines, and 4) voids that are associate with karst. In limestone and marble mining, void collapse has been linked to the dewatering of shallow aquifers in the vicinity of quarries. We have investigated three locations where voids were found beneath highways and represent potential collapse hazards.

An AGI Supersting R8 IP instrument with a multi-channel Swift dual mode automatic multi-electrode cable was used for the surveys (www.agiusa.com/supersting.shtml). The cable was equipped with 56 electrodes that could be deployed at up to 6 m electrode spacing. Dipole dipole arrays were used for 2D surveys; pole dipole arrays were used for 3D surveys.

Case Studies

Interstate 70, Cambridge, Ohio

On March 5, 1995, a sinkhole approximately 3.5 m in diameter opened in the eastbound lanes of Interstate 70 near Cambridge, Ohio. Three cars and a truck entered the sinkhole before traffic could be stopped. One injury resulted from the collapse and the roadway was closed 3.5 months for repairs. The segment of highway where the collapse occurred is about 20 m above an abandoned underground coal mine in the Upper Freeport Coalbed. Subsidence of strata above the mine together with the piping of unconsolidated overburden material into the mine conspired to weaken the roadbed and resulted in its collapse. The highway was stabilized by building a ground-level bridge over the most failure prone areas and injecting grout of various compositions into 1800 holes drilled into the highway (Fig. 1)

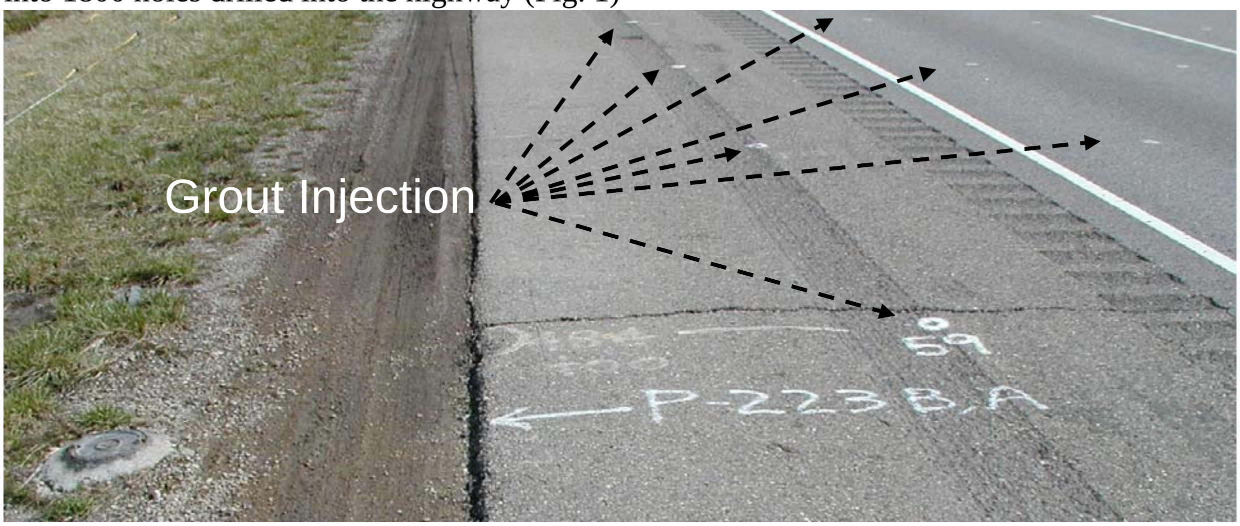


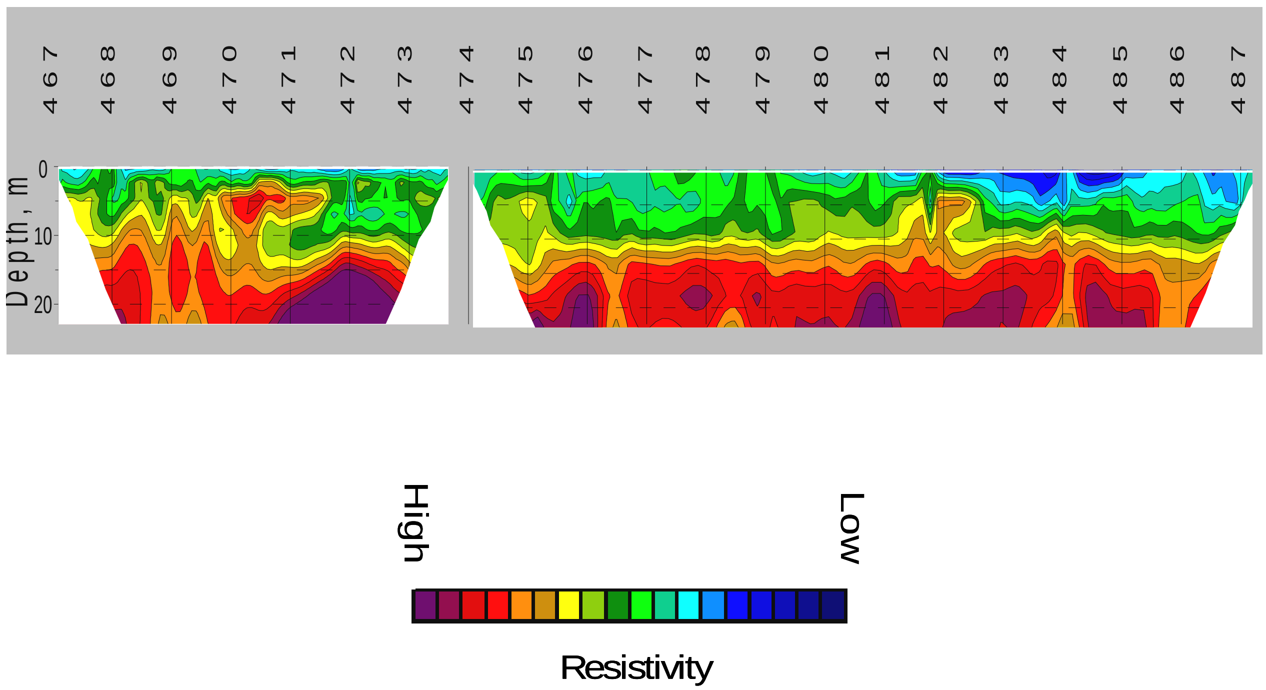
Figure 1 Grout injection locations in the eastbound lane of Interstate 70 near Cambridge, Ohio.

Subsequent to the collapse, this segment of Interstate 70 has served as a testbed for geophysical techniques aimed at identifying near-surface voids. Methods that have been tested at this site include:

1) surface ground penetrating radar (GPR);
2) cross-hole GPR;
3) high resolution surface shear wave measurements;
4) spectral analysis of surface waves (SASW);
5) cross- hole seismic shear wave velocity logging (CSL); and,
6) cross-hole seismic tomography measurements (CST).

In 2002, seven years after the road closure and after the above geophysical techniques were tested at the site; NETL conducted a DC resistivity survey along the outside shoulders of the westbound and eastbound lanes (Fig. 2). The intent of this survey was to determine if DC resistivity could provide a better representation of subsurface conditions than the geophysical techniques already mentioned. At a minimum, DC resistivity was expected to provide information that when combined with results from other methods would provide a more comprehensive understanding of subsurface conditions.

Figure 2 2D resistivity survey conducted along the shoulder of eastbound Interstate 70 near Cambridge, Ohio.



The I70 survey was conducted in early spring when the soil was still damp from recently melted snow. At this time of year, the soil along highways was especially conductive because of the de-icing chemicals that were applied during the winter. The high conductivity of the near surface required that current injections be reduced to 200 mA to avoid overloading the resistivity instrument. Figure 3 shows the vertical distribution of resistivity beneath the outside shoulder of the eastbound lane. The bedrock surface can easily be seen as the interface between the predominantly blue and green colors of the relatively more conductive unconsolidated cover and the relatively more resistive yellow-orange-red of the bedrock. Resistive areas within the unconsolidated cover are interpreted to be unsaturated sand lenses, grout fingers, or voids. Two narrow, vertical conductive zones in the unconsolidated cover at station 472 and left (west) of station 482 are thought to be the result of current channeling by conductive well casings. The highway collapse occurred just to the left (west) of station 484. The model resistivity section indicates an offset in the bedrock surface at this location. This agrees well with seismic data (Guy et. al., 2003), which indicated a normal fault and an offset in the bedrock surface at this approximate location. The model resistivity section also indicates that the bedrock at this location is less resistive. A subsidence fracture would be expected to provide a near-vertical conduit for groundwater flow into the mine void. With the flow of groundwater into the mine,

Figure 3 Model 2D resistivity section along the right shoulder of the eastbound lane of Interstate 70 near Cambridge, Ohio

the piping of unconsolidated sediments into the fracture zone and the mine void would also be anticipated. Both processes would reduce the resistivity of the fractured bedrock.

By using the features of the known collapse area as a model, other potential collapse areas can be identified. The feature that most resembles the known collapse zone is located between stations 476 and 477. This feature displays a pronounced drooping of the conductive cover into the bedrock and a vertical conductive feature within the bedrock. Seismic results (Guy et al. 2003) also show a corresponding depression in the bedrock surface at this location. Other areas with similar features include a narrow zone between stations 478 and 479, a wider zone at station 486, and a very wide zone that extends from west of station 469 almost to station 471. Seismic results showed an irregular bedrock surface between stations 478 and 479, but no faults were interpreted. Seismic indicated two normal faults at station 486 and five normal faults between stations 469 and 471. All of these areas should be considered as potential collapse zones. A large offset in the bedrock surface is evident at station 475, and is accompanied by a small, resistive body in the unconsolidated cover. The resistive zone may represent a void, a grout finger that is now filling a void, or a cross section through the sand deposit from a paleostream channel. Four normal faults in the bedrock have been interpreted from the seismic results for this area.

The results of this survey suggest that DC resistivity is at least as valuable as seismic for identifying subsurface features that are indications of highway collapse potential. Certainly, resistivity results are more easily interpreted. As is the case with any geophysical technique, corroboration using other geophysical methods or drilling is required.

Marble Quarry, Carroll County, Maryland

At approximately 2:00 AM on March 30, 1994, a vehicle traveling on Route 31 near Westminster, Maryland crashed into a large sinkhole that had suddenly formed in the highway. The sole occupant of the vehicle was killed. Highways, buildings, and a railroad in proximity to a marble quarry in this area have been prone to sudden and sometimes catastrophic sinkhole development. Sinkhole development is common in the marble bedrock, especially in the cone of depression caused by groundwater pumping at the quarry. Road maintenance crews have to be especially vigilant because sinkholes with large offsets can form suddenly and with little or no warning.

In 2003, NETL conducted a DC resistivity survey along a 500-m, sinkhole-prone segment of Medford Road, a two-land blacktop road that is less than 200 m from the marble quarry (Fig. 4). Results of the resistivity survey (Fig. 5) provided a good depiction of the bedrock surface as well as the conductive clay and soil overburden. Most sinkhole occurrences were found to be on or near the edges of the bedrock platform that was interpreted from resistivity data. This finding was unexpected and 3D resistivity surveys are planned for sinkhole areas to better understand the relationship between sinkholes and the bedrock platform.

Figure 4 The location of a DC resistivity profile collected along a sinkhole-prone segment of Medford Road is depicted in yellow.

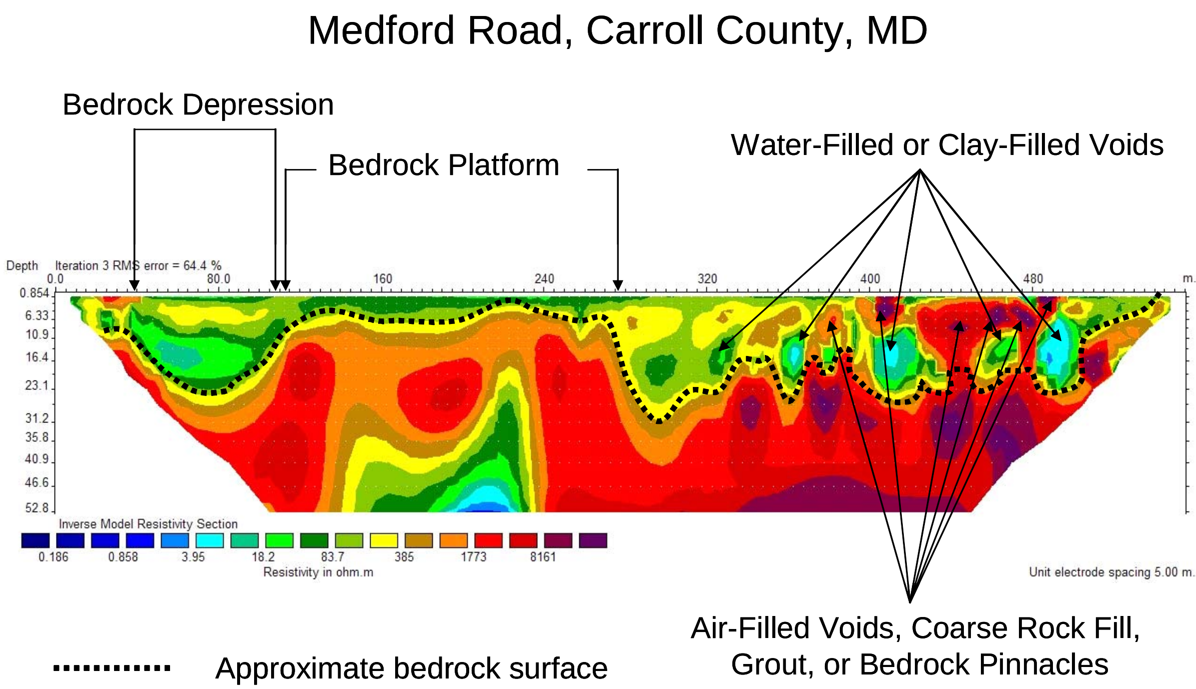


Figure 5 Model resistivity section for segment of Medford Road.

Limestone Quarry, East-Central Pennsylvania

A large limestone quarry in east-central Pennsylvania is within 200 m of a small river (Fig. 6). Dye tracer tests indicate that water from the river is flowing into the quarry, presumably via solution cavities. Pumping water from the quarry back into the river costs quarry operators about $5000 per month, an operating cost that they would like to avoid. Prior to this study, the quarry operators have unsuccessfully attempted to prevent river water from entering the subterranean passages by sealing the river bank adjacent to the quarry.

Figure 6 Map showing the location of a large, limestone quarry and adjacent river.

In 2002, NETL acquired a resistivity profile along a segment of highway (Fig. 6) between the river and the quarry (Fig. 7). The intent of this survey was to locate voids that may serve as conduits for the flow of water into the quarry. Figure 8 is the model resistivity data, which indicates three resistive areas that were interpreted to be potential voids. Subsequent drilling by the quarry operator found that:

- target 1 was a limestone pinnacle,
- target 2 was a collapsed cave (broken rock and clay), and
- target 3 was a large open cave.

Target 3 was found to be a cave with rooms up to 7-m (20 ft) high. Water was encountered while drilling target 3 and two small catfish were blown out of the drill hole. This suggests that the cave extends beneath the road to the river. Additional drilling by the quarry operator found that the cave extended to the left of target 3; 30 cubic yards of concrete were required to fill the void. Unfortunately, the filling of this cave has not decreased the flow of water into the quarry significantly.

Figure 7 Red flags denote the location of resistivity survey. Active sinkhole area is shown by black circle.

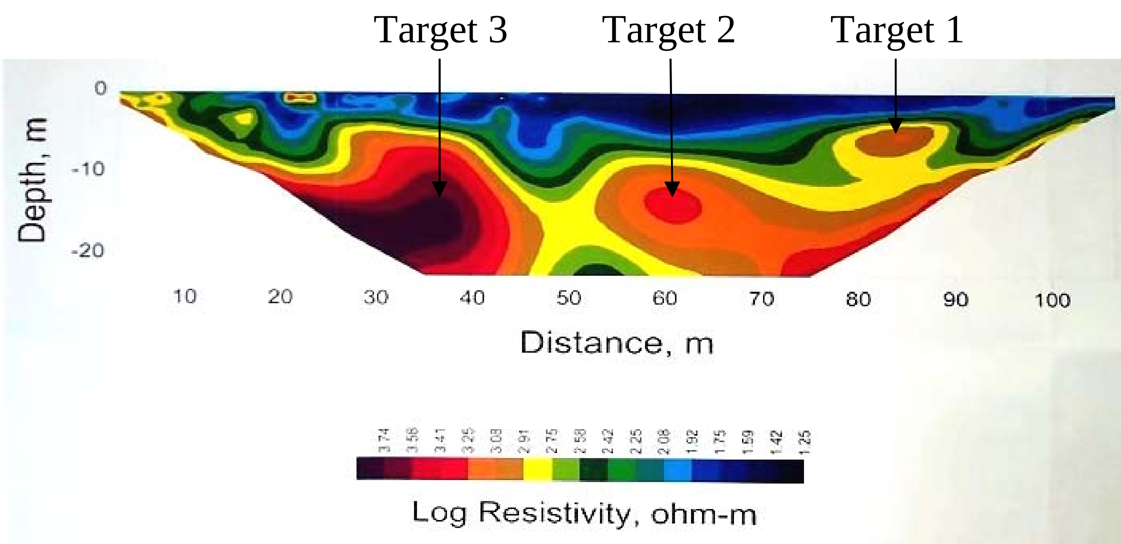


Figure 8 Model resistivity section for profile along Martindale Road.

The resistivity profile in Figure 8 crossed a sinkhole (Fig. 8, distance 20-24 m at 0-2 m depth) that had been repaired by PennDOT (Fig. 9). The sinkhole was filled with coarse rock that is depicted as a near-surface resistive area above a bedrock depression in Figure 8.

Figure 9 The resistivity survey crossed an active sinkhole that had been filled by PennDOT prior to the study.

Conclusions

DC resistivity is especially useful for highway studies because it is relatively unaffected by traffic (unlike electromagnetic techniques). However, resistivity surveys must be carried out parallel to the roadway unless traffic can be detoured or stopped. DC resistivity was found to be an effective technique for detecting:

1. bedrock surfaces beneath conductive cover,
2. mine subsidence features, and
3. air-filled or water-filled voids.

In the three case studies, DC resistivity was able to accurately detect bedrock surfaces (as verified by drilling and seismic results). Further, DC resistivity detected mine subsidence features (as verified by seismic results) in the I70 study. The limestone quarry study demonstrated the ability of DC resistivity to identify solution cavities in karst terrain (verified by drilling).

Reference Cited

Guy, Erich D, Richard C. Nolen-Hoeksema, Jeffrey J. Daniels, Thomas Lefchik, 2003, High-resolution SH-wave seismic reflection investigations near a coal mine-related roadway collapse feature. Journal of Applied Geophysics, V. 54, pp. 51-70.